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High-resolution Full Wavefield Inversion model building in deep-water environment: A case study in the Orphan basin.

Eric Frugier, Tiago Alcantara and Bruno Virlouvet
PGS
Nicholas A. Montevecchi, Deric E. Cameron and Richard Wright
Nalcor Energy Oil & Gas

Summary

The 2018 Tablelands GeoStreamer seismic survey was acquired in partnership with Nalcor, PGS and TGS in the Orphan basin, offshore Canada. The partnership pioneered a proof of concept project over a deep-water 500 km^2. The project demonstrated the benefits of building a Full Wavefield Inversion (FWI) driven velocity model using dual-sensor data. This paper presents the FWI velocity model building workflow, which produced a high-resolution and geologically consistent velocity model. The model was later used in Kirchhoff migration, Least-Square Wave-Equation migration and for quantitative interpretation purposes.

Introduction and geological setting

The Orphan basin is located in the north of the Grand Banks, approximately 400 km North East of St. John's in Canada. While in an early exploratory phase, this basin has shown some potential. Seismic images suggest the presence of Jurassic source rocks as well as hydrocarbon entrapments in Tertiary, Cretaceous and upper Jurassic leads.

One of the few wells in the area, the Great Barasway well, is located at the center of our case study. It sits on a structural high and exhibits Amplitude Versus Offset (AVO) anomalies in the Cretaceous and upper Jurassic units (Figure 1). Though unsuccessful, it did confirm the presence and quality of reservoirs, as well as two formations that constitute source rocks in adjacent basins, the Tithonian and Kimmeridgian age formations.

Early exploration efforts relied on the quality of seismic images. Least-Square Migration provides a more reliable estimate of reflectivity, reducing uncertainty associated with reservoir characterization. It requires an accurate velocity model and an approximate representation of the earth's reflectivity (Lu et al., 2017). The velocity model provided by FWI, using time domain data, enables accurate high-resolution models free of high frequency assumptions.

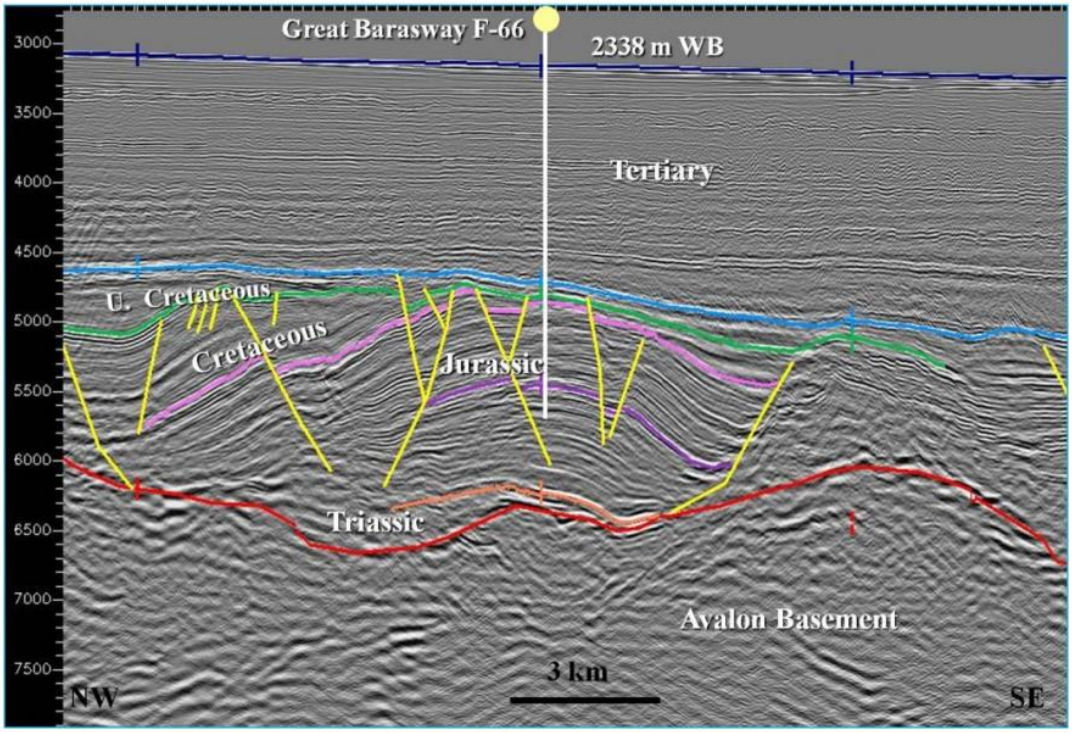

Figure 1. Great Barasway F-66 geological background (Enachescu et al, 2010).

FWI implementation

Full Waveform Inversion (FWI) is a nonlinear problem that generates high-resolution velocity models by minimizing the misfit between observed and modeled shot data. The initial model is iteratively improved using a sequence of linearized inversions.

While conventional FWI relies on inverting for the refracted waves, the FWI method used in this example exploits the full wavefield. In deep-water environments, the refracted energy is limited due to a lack of long offsets, and most of the inversion is driven by the reflected energy. This allows us to update velocities much deeper in the subsurface.
Modeling is performed using the acoustic, two-way wave equation with pseudo-analytical extrapolation in time domain (Ramos-Martinez et al., 2011). The inversion uses a normalized form of the Born scattering kernel to compute the FWI gradient (Tarantola, 1984) through a variation of an Inverse Scattering Imaging Condition (ISIC). This gradient eliminates the migration isochrones that would generate high wavenumber artifacts which dominate conventional cross-correlation FWI gradient results (Ramos Martinez et al., 2016).

Additionally, we use a variable density model, necessary to model reflections in the absence of strong velocity contrasts. This results in better matching between modeled and recorded seismic events.

FWI uses minimally processed shot gathers and can be run early in an imaging project. Therefore a high-resolution velocity model can be created in parallel with the time pre-processed data, minimizing the impact of model building on project turnaround (Figure 2).

FWI velocity model building workflow and results

FWI relies on three key components: a wavelet, input data and an initial velocity model.
The wavelet was extracted from the raw data.

The input data, was prepared as follows:

1) Noise is removed from the raw shot data
2) Phase analysis is performed on the denoised data in octave panels. This indicated that the FWI could be started in the 2 Hz to 4 Hz bandwidth.
3) A second pass of noise attenuation is run targeting these low frequencies.

To maintain phase consistency with the FWI wavelet we also convert the data to minimum phase. Starting inversions with the lowest possible frequency contained in the GeoStreamer data and an updated velocity model reduces the risk of cycle-skipping.
For this purpose, we created a VTI depth velocity model from the raw data by running several wavelet shift tomography updates (Sherwood et al., 2008 and Sherwood et al., 2011). Initial anisotropic parameters were extracted from well information and later updated through tomographic inversion.

We recursively inverted using increasing bandwidths from 4 Hz to 25 Hz (Figure 2). For each bandwidth, the velocity model was updated so that the misfit between recorded and modeled shots was reduced. The process was then iterated until the FWI cost function flattens. The quality control metrics of convergence were based on both amplitude misfits and cross-correlation between modeled and field data.

After each frequency bandwidth inversion, additional quality control was performed in both data and image domains to ensure that model resolution and migrated image are improved. Such QCs included modeled shots and receiver gathers compared to recorded data, FWI velocity perturbation, migrated gathers and stacks before and after the FWI inversion.

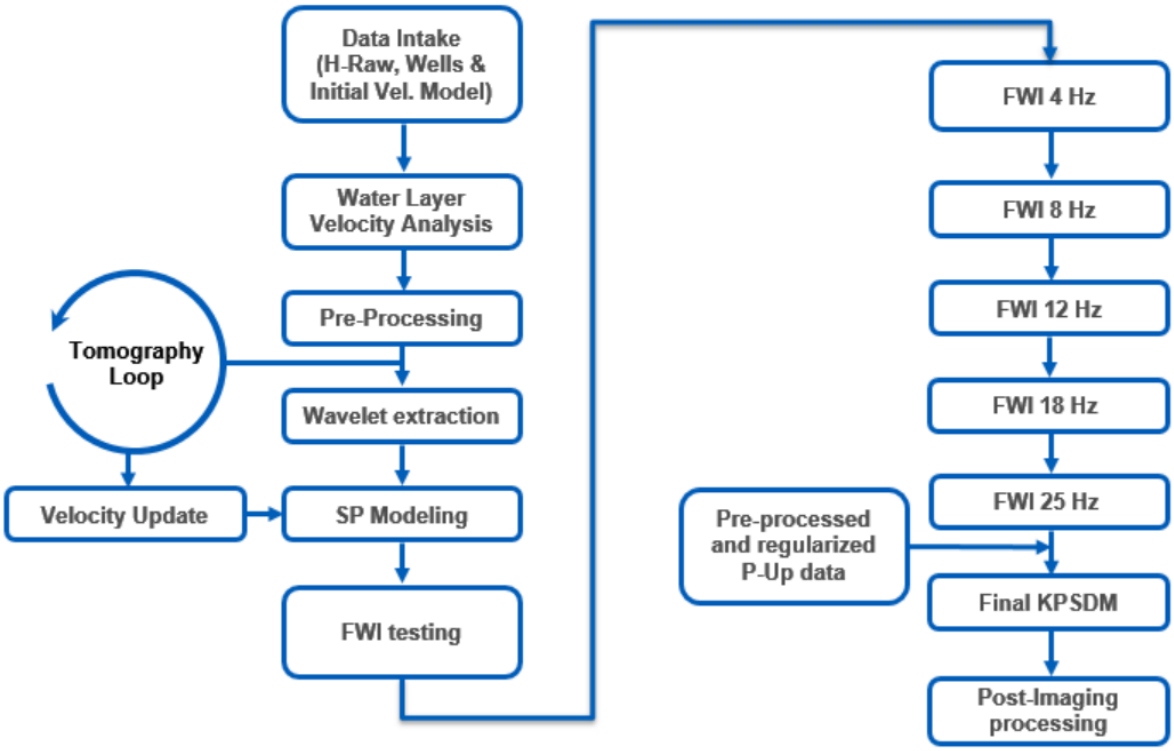

Figure 2. FWI velocity model building workflow.

The resulting FWI velocity model had fine resolution capturing the small-scale geological features in the deeper, Tertiary section (Figure 3). Using reflection energy, several velocity inversions were modeled, particularly in the shallow overburden. We also observed that our updated velocity model closely follows the regional structural trend in the deeper Jurassic section, despite the limitations of the offset coverage and illumination.

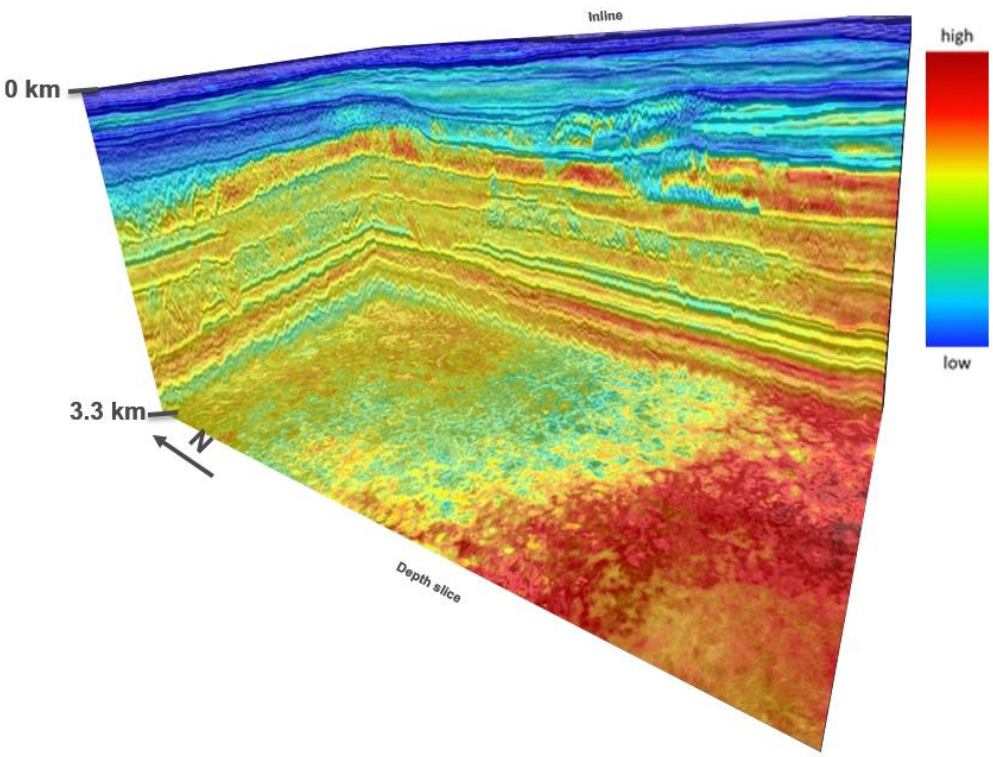

Figure 3. 3D view of the velocity model in the Tertiary/Cretaceous section after the 25Hz FWI update.

The high-resolution FWI velocity model was used in Kirchhoff Prestack Depth Migration and Wave-Equation LSM (Alcantara et al, 2020), leading to better-defined structures and faults in the deeper sections, which mitigate potential drilling risks.

Lastly, the FWI model was used in quantitative interpretation for the Low Frequency Model (LFM) in elastic property generation (Martin and Reiser, 2019). It enabled an accurate match between absolute acoustic inversion and the Great Barasway well log.

Conclusions

A unique implementation of FWI was successfully used on deep-water, dual-sensor seismic data from the Orphan basin, inverting for both reflected and refracted wavefields. The results capture high-velocity contrasts and velocity inversions in the geologically complex overburden that were missing from the initial model.

The ultra-low frequency dual-sensor data set enabled FWI to start from the 2-4 Hz frequency band, reducing the risk of cycle-skipping, and allowed the velocity model building to start in parallel with the pre-imaging phase of the project. The model was then used to provide high-end depth imaging, including Kirchhoff and Wave-Equation Least-Squares migrations. Finally, our model was used in elastic property generation, all of which reduced uncertainty.

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